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CONTROLLED MULTIBODY DYNAMICS SIMULATION FOR LARGE SPACE STRUCTURES

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MULTIBODY DYNAMICS DISCIPLINE

The multibody dynamics discipline involves the large relative motions of connected flexible bodies. Thus, the configuration of the multibody system is time-varying, generally resulting in time-varying inertial properties and sometimes in time-varying stiffness properties. Hinge connections between the bodies are necessary to enable the changing relative orientations. Because there are multiple bodies, it is quite likely there will also be multiple control systems with multiple objectives. Multibody dynamics finds application in various fields. Many applications impose constraints on the multibody system and the handling of these is a critical aspect of the discipline.

o DEFINITION: Interconnected Flexible Body Dynamics With Time Varying Relative Orientations

- Time Varying Stiffness and Mass
- Hinge Connections of Various Types
- Multiple Control Systems

o APPLICATIONS:

- Mechanisms
- Unfolding Deployment/Retraction
- Articulation

o CONSTRAINTS

- Motion Limiters, Mechanical Regulators
- Connect/Disconnect
- Lock/Unlock
- Robotic Hand-Off

THE ROLE OF MULTIBODY DYNAMICS SIMULATION ANALYSIS IN CSI DESIGN

Four roles are here identified for multibody dynamics simulation. Use of this simulation early in the design process can be most effective as it can reveal design shortcomings before commitment to a design concept. Multibody simulation can be used to address performance degradation, constraint violation and stability. Invariably the simulation models are more refined then the design models and can thus be used to judge the suitability of the design models. The simulation models usually incorporate modes left out of the design models, thus addressing "spillover", uncertainties in structure, controller, sensors and actuators, and nonlinearities which are often neglected in design.

o IDENTIFIES TECHNICAL ISSUES EARLY IN DESIGN PROCESS

LESS EXPENSIVE THAN EXPERIMENTATION
CAPABLE OF PARAMETER STUDIES WITH REFINED MODELS

o ESTABLISHES CONTROLLER PERFORMANCE DEGRADATION

MODAL TRUNCATION, UNCERTAINTIES AND NONLINEARITIES

o ESTABLISHES VIOLATION OF CSI DESIGN CONSTRAINTS

STRUCTURAL MEMBER BUCKLING
ACTUATOR OUTPUT EXCEEDANCE

o EXAMINES STABILITY OF DESIGNED SYSTEM

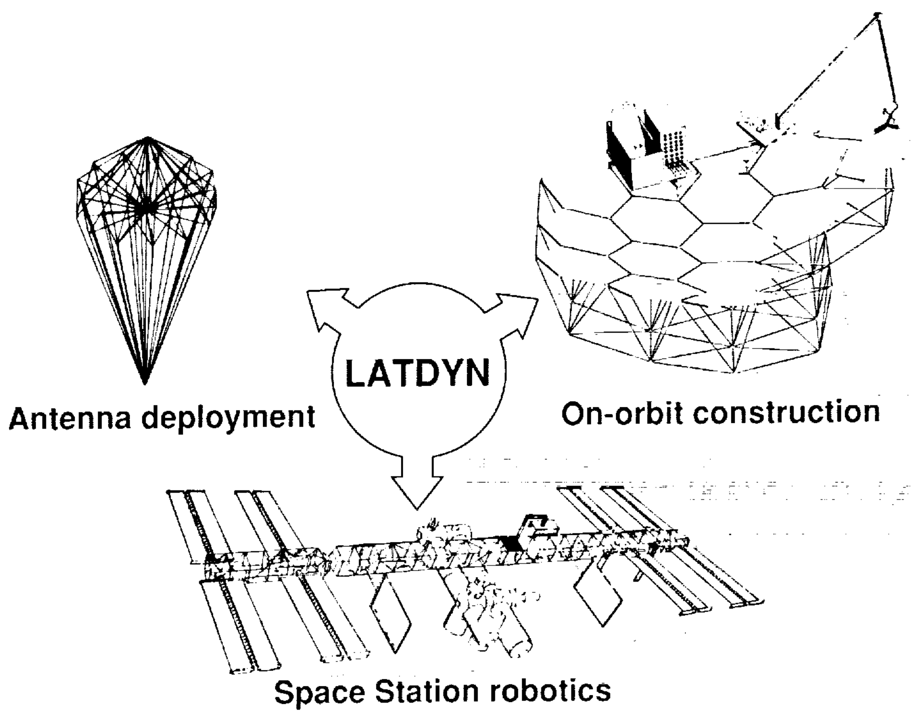
ACTUATOR AND SENSOR PLACEMENT
LINEAR DESIGN ASSUMPTIONS

LATDYN CAPABILITIES

The LATDYN (Large Angle Transient DYNamics) code is a simulation tool for controlled multibody dynamics. The code is finite element based with the present version having a limited element library consisting of mass, spring, damper and beam elements. The user models each body with finite elements, rather than with truncated modes or other function sets which have to be generated outside the multibody program.

Control laws are input through a FORTRAN-based command language which gives the user internal access to the code from an external position. Further details on the program architecture are given in the chart on LATDYN architecture.

Practicalities of control implementation can also be modeled such as actuators, friction and time delay in digital control. Two and three dimensional versions are available and results from these are presented herein. Additional information on the code is available in references 1 - 3.



LATDYN CAPABILITIES

- o SIMULATION ANALYSIS TOOL FOR LARGE MOTIONS AND DEFORMATIONS OF CONTROLLED MULTIBODY STRUCTURES FOR,

  ASSEMBLY DYNAMICS, ARTICULATING COMPONENTS, ROBOTIC OPERATIONS

- o FINITE ELEMENT BASED STRUCTURAL MODELING

  RIGID OR FLEXIBLE COMPONENTS
  ARBITRARY GEOMETRY

- o EXTENSIVE CONTROLS MODELING

  FORTRAN BASED COMMAND LANGUAGE PERMITS SIMPLIFIED USER INPUT OF CONTROL ALGORITHMS

- o ACTUATOR AND MOTOR MODELING

  FRICTION AND TIME DELAY

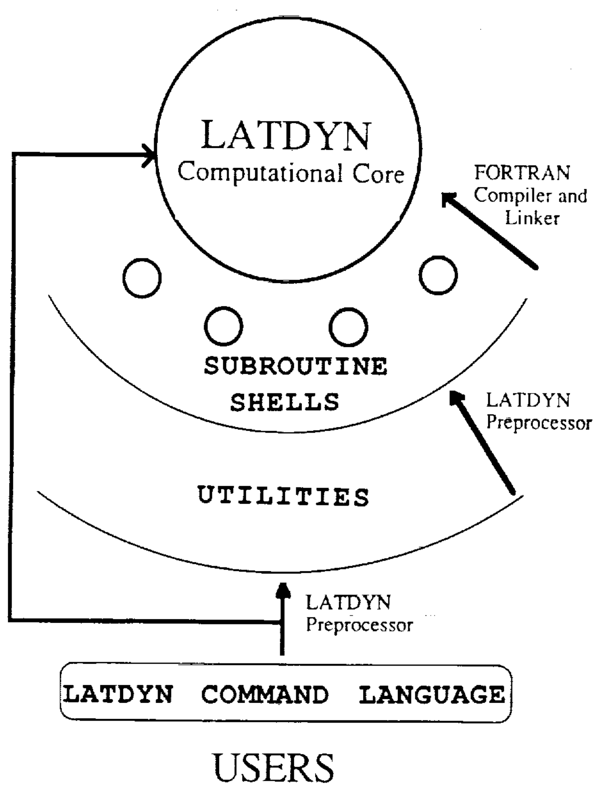
- o 2-D VERSION DEVELOPED IN 1986

- o 3-D WORKING VERSION OPERATIONAL

LATDYN ARCHITECTURE

For the structural part of the modeling, user commands resembling that of a typical general purpose finite element program are employed. However, for controls, the commands take on a somewhat different character. The user writes the control law equations in FORTRAN within a command statement using a defined protocol to access utilities residing in the LATDYN pre-processor. (Since most users are well acquainted with FORTRAN this is a natural language to use.) The pre-processor generates complete FORTRAN code which is then placed in empty subroutine shells. This resembles the user-written subroutines employed by other programs, but has the distinct advantage of relieving the user of the burden of understanding the complex operations of the code. The user need not be concerned with what subroutines are created, nor how data are transferred within the code. This and many other functions are performed automatically. Finally the generated code is compiled and linked to the LATDYN computational core.

Furthermore, the user can create his own variables and can readily specify logic conditions under which commands are to be activated or deactivated. This is an important aspect for control actuators which are only activated once prescribed conditions are exceeded or can become saturated as in the case of momentum exchange devices.

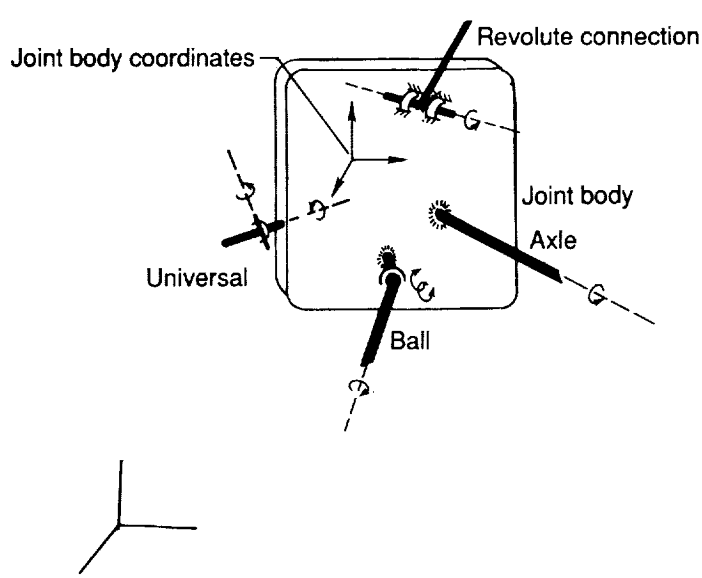


GENERIC JOINT BODY WITH VARIOUS TYPES OF HINGE CONNECTIONS

The class of structures to be treated by this program is joint dominated. That is, the mass of the interconnecting joints between the bodies represents a significant portion of the total mass and the orientation of the joint's hinge lines plays an important role in determining structural behavior. It is thus reasonable to construct the finite element program with the joints as a part of the element connectivity. This avoids numerical problems which can arise due to what might be called "the tail waging the dog" phenomenon. Furthermore, since large angular rotations are not vectors, connectivity relationships could be time varying and quite complex. The use of hinge bodies circumvents these connectivity complications.

A generic hinge body with several members connected to it through various types of joints is depicted in the figure. Accommodations for hinge connections to various members connected to the hinge body are built into the formulation.

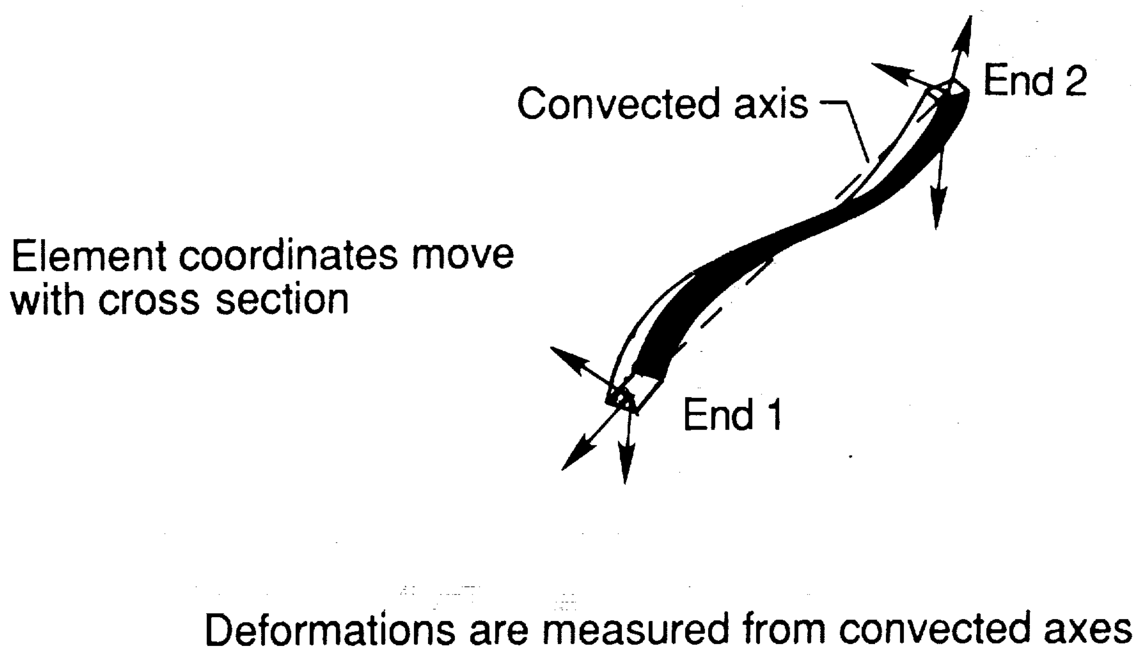
A Cartesian coordinate system is used to measure three translations of a designated point on a hinge body and a transformation matrix provides the orientation of three orthogonal axes embedded into the hinge body. Members are assumed to be hinge-connected to a hinge body. The connecting hinge line is embedded into the hinge body and is related to the hinge body axes through a fixed transformation matrix Γ. The rotation Θ about the hinge line is time varying.



DEFORMED FINITE-ELEMENT AND ELEMENT COORDINATE SYSTEMS

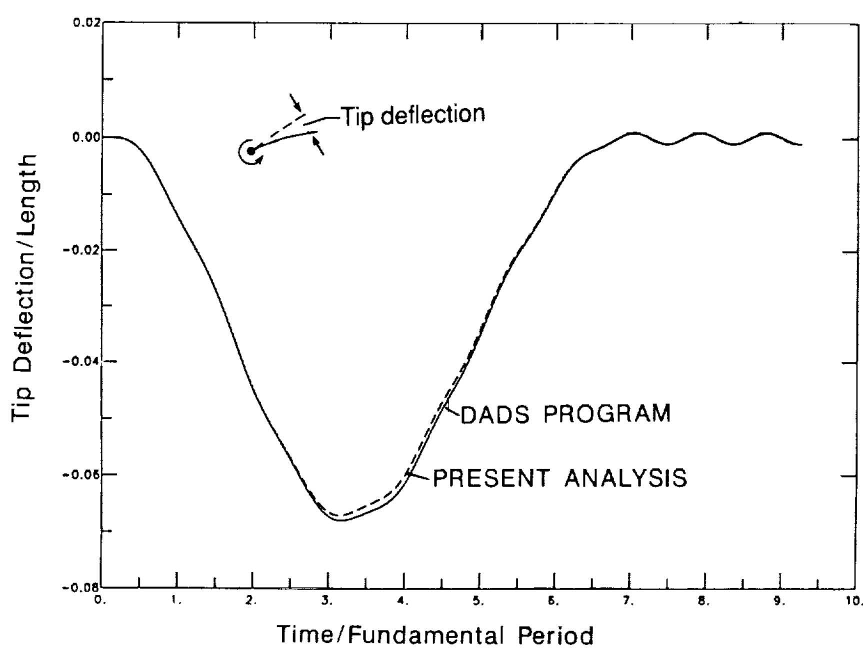
Each structural member is divided into finite elements. A typical deformed element is shown in the figure. The orientation of the element at its ends is monitored by means of a two-element coordinate system, one at each end. These coordinates move with the element. The x-axis of the element system is tangent to the element at its end and the other two orthogonal axes are parallel to the principle axes of the element cross section. The orientation along the length is found from an assumed polynomial shape function as in any finite-element analysis.

A convected coordinate system is used to define a reference for measuring element flexural deformations. This separates rigid body and deformable motion. As shown in the figure, the convected x-axis connects the end points of element. Its other two orthogonal axes roll with the element.



COMPARISON OF RESULTS FOR FLEXIBLE BEAM SPIN-UP ON A PLANE

A flexible rotating beam, with a one hertz fundamental frequency is accelerated to a constant angular velocity in six seconds. The results of the LATDYN program are compared with those from a commercial code known as DADS. (See reference 4 for further details on this code.) Results are in excellent agreement with only a slight deviation during the transient region. The LATDYN model uses two finite elements, but one would have sufficed. The DADS result can be found in reference 5.

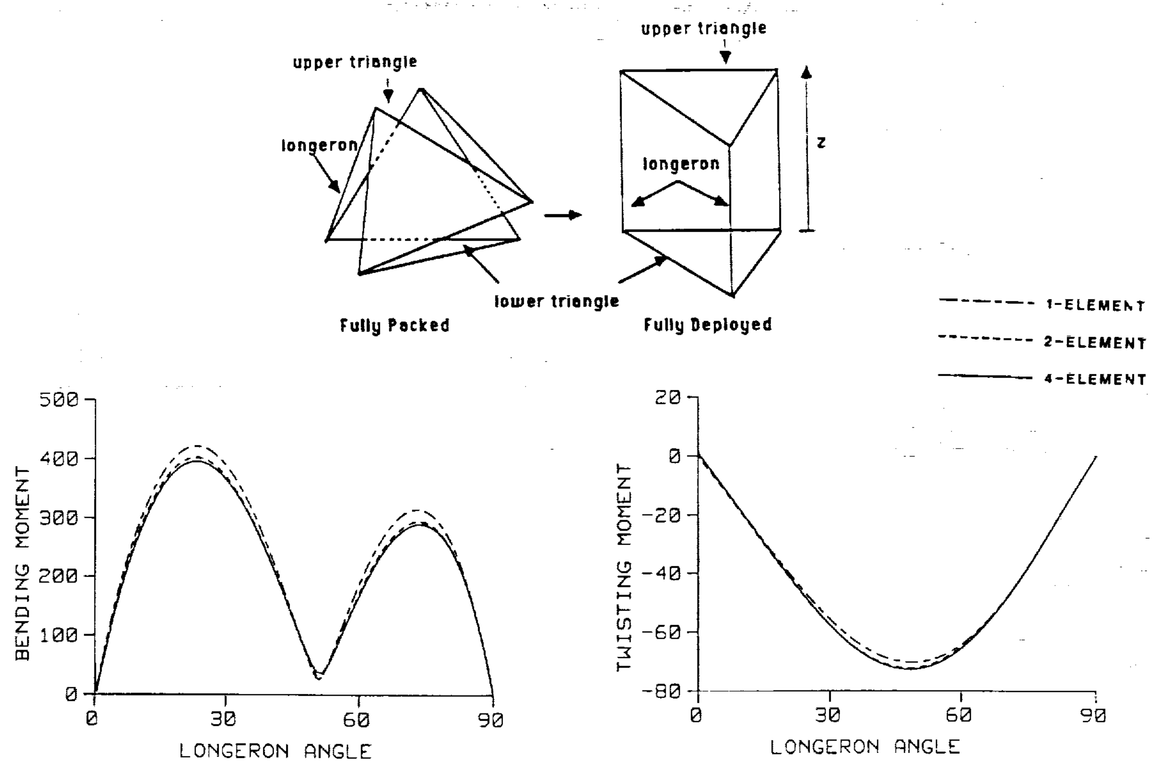


MINI-MAST DEPLOYMENT

The Mini-Mast is a 20 meter long, triangular cross-section, three longeron truss. The truss members are of graphite-epoxy and the joints, which contain the hinges between the members, are titanium. Reference 6 provides further details on the truss properties. The Mini-Mast derives its name from the longer 60 meter mast formerly planned as an on-orbit experiment deployed from the Space Shuttle's cargo bay. The Mini-Mast was designed and fabricated by the ASTRO Corporation.

The upper portion of the chart shows a single bay of the truss. Deployment proceeds by rotating the upper triangle 100 degrees counterclockwise about the vertical axis till the longerons are in a vertical orientation. Though not shown in the figure, a diagonal exists on each face of a truss-bay. The diagonal has a folding hinge at its mid-length and locks-up following deployment.

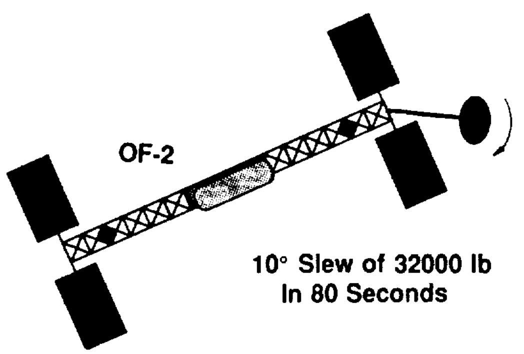
The hinge angles are designed so that when fully packaged, as it would be in the cargo bay, the members are stress free. Also, when fully deployed, the members are stress free. However, during deployment or retraction, the members deform considerably. This is seen in the bottom portion of the chart both in the bending and twisting moments of the longeron.



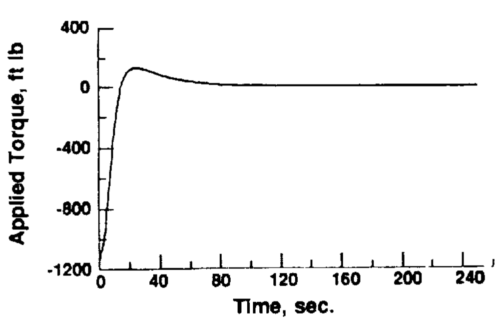
LATDYN Simulation of Controlled Robotic Slewing
Operation on Space Station

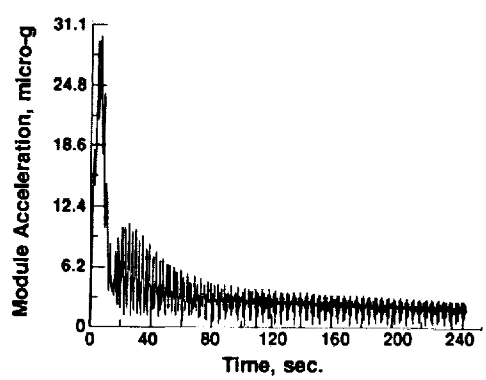
The LATDYN code is used to simulate Space Station response to a 10 degree slew of an RMS-like arm carrying a 32,000 pound payload. The slew operation is performed very slowly, taking 80 seconds. (At this rate a complete 360 degree operation takes about the half an orbit of the station.)

A torque motor at the arm's root drives the operation and, using angular rate feedback, suppresses the arm's vibration. As shown in the figure, the simulation provides the torque history which can then be used to improve the design of the torque motor, gimbal, or truss members. Also provided is the resulting module micro-gravity environment which shows that even though the arm controller suppresses arm vibration, as seen in the torque history, the modules continue to ring for a long time. Clearly more is required if the module micro-gravity environment is to be further reduced.



- Perform 10° slew using RMS-like arm
- Torque motor control law performs slew and suppresses payload vibration
- Generate torque history for future loads analysis
- Examine micro-g environment



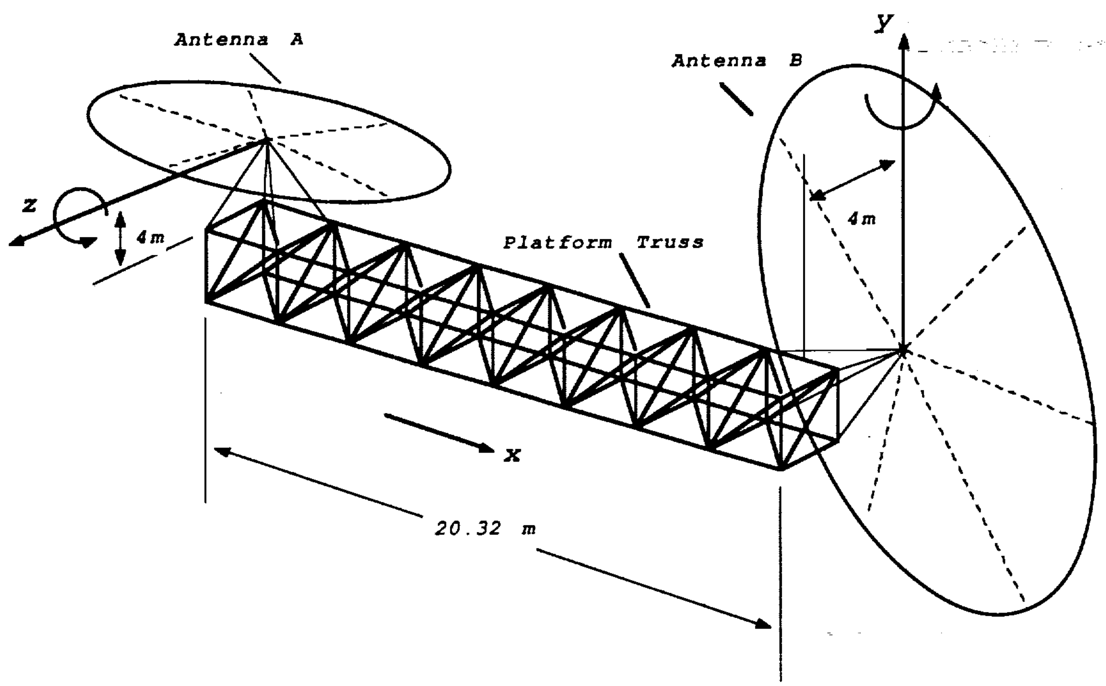


Potential CSI Test Article

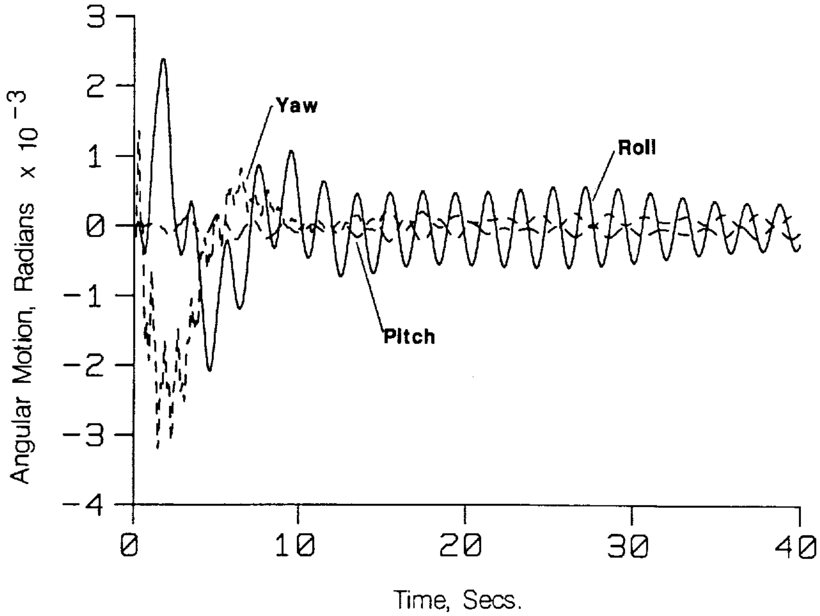
A potential CSI article is depicted in the first of the next three charts. Though not shown to scale, the truss contains ten inch cubic bays. In the LATDYN simulation, the larger antenna, labeled B, is rotated 30 degrees about the vertical y axis (yaw rotation) and the response at the truss center of gravity is studied under two conditions; without an attitude control system and with an attitude control system.

In the absence of an attitude control system, the yawing of the antenna produces a yaw of the spacecraft due to conservation of angular momentum and a roll of the spacecraft due to the offset of the antennas from the truss-beam neutral axis. In addition, gyroscopic effects result in a smaller pitching motion of the craft. Angular feedback control on the motor which drives the antenna yaw helps to suppress some of the ensuing vibrations. Its design being based on rigid body assumptions, it does a poor job of this.

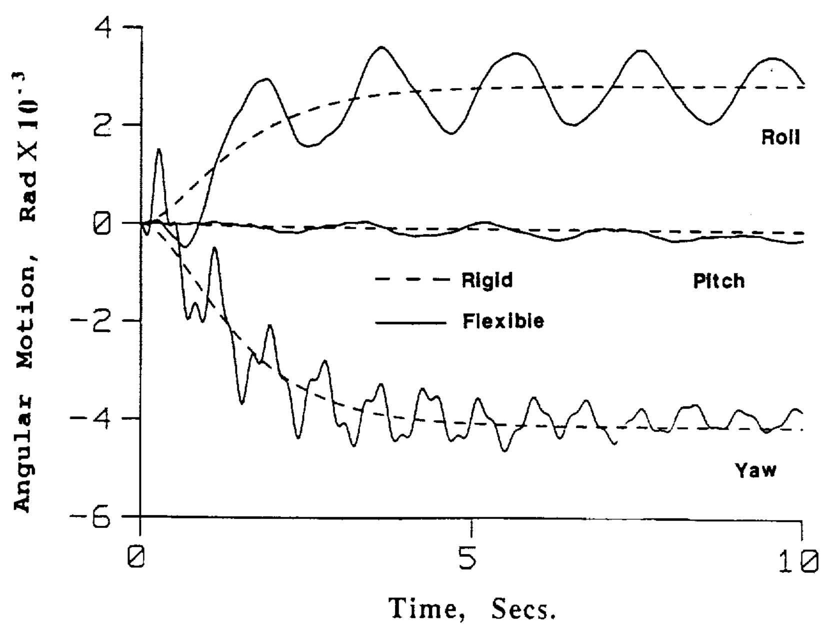
In the presence of an attitude control system, the overall attitude of the spacecraft is kept along its nominal path, but vibrations of the flexible craft are significant. Additional actuators are necessary to reduce these vibrations.



SPACECRAFT RESPONSE AT TRUSS C.G. DUE TO 30 DEG. LARGE ANTENNA YAW - WITH ATTITUDE CONTROL



SPACECRAFT RESPONSE AT TRUSS C.G. DUE TO 30 DEG. LARGE ANTENNA YAW - WITHOUT ATTITUDE CONTROL



Requirements for Multibody Benchmark Experiments

The next two charts address the need for multibody experiments which can be used to determine their accuracy and reliability. Such experiments should be relatively inexpensive and easy to assemble and to change out components. Most importantly their motions when rigid components are used must be significantly different from their motions when flexible components are used.

One such experiment is shown. It consists of three nearly rigid members and one pendular member which can be either rigid or flexible. Response of the pendular member tip is shown both for a flexible and a rigid member. The responses are desirably different, even having a somewhat different fundamental frequency.

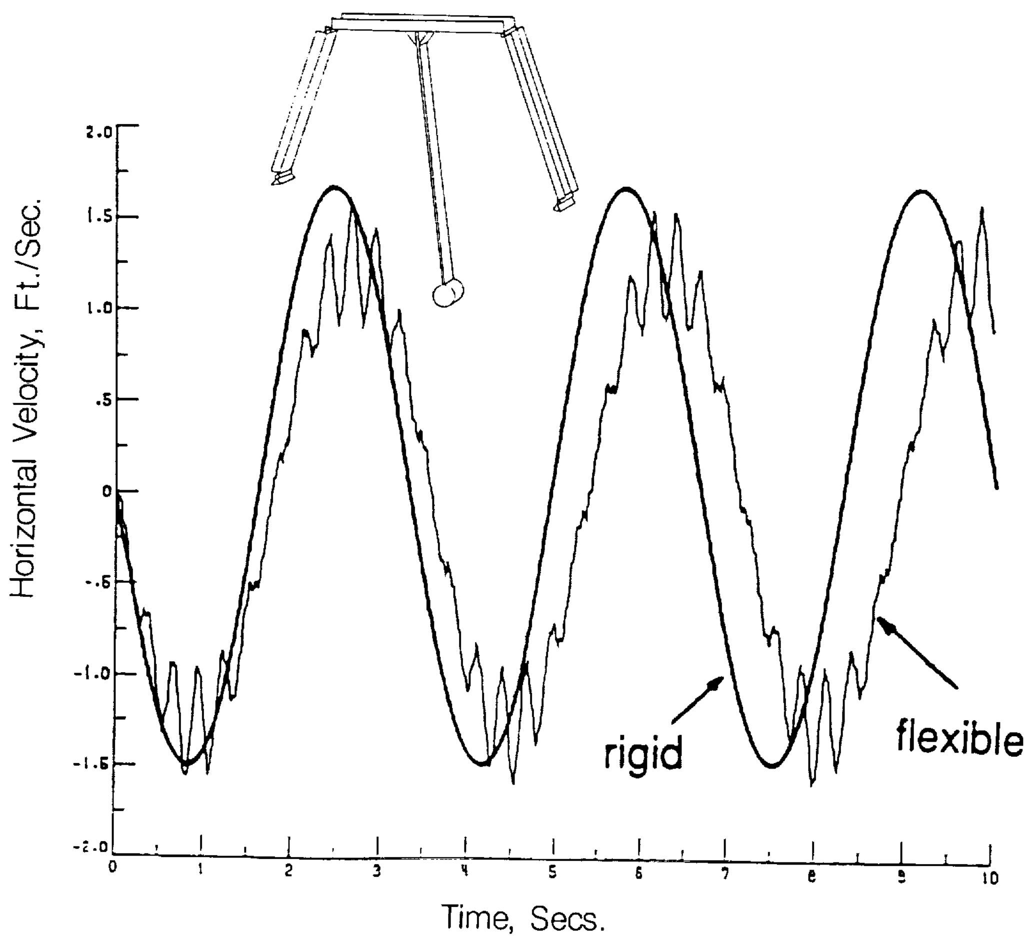
The dimensions of the members and the tip mass have been chosen so as to make the device stable, but these can be changed to come as close as desired to instability. This represents an important test for simulation codes, since they may predict stability when the system is unstable or stable when it is not.

- **INEXPENSIVE**

- **EASY TO ASSEMBLE AND CHANGE COMPONENTS**

- **FLEXIBLE MOTION SIGNIFICANTLY DIFFERENT FROM RIGID BODY MOTION**

FLEXIBLE PENDULUM MULTIBODY EXPERIMENT



CONCLUDING REMARKS

- o MULTIBODY RIGID/FLEXIBLE COUPLED EXPERIMENTS ARE REQUIRED FOR SIMULATION VALIDATION

- o THOUGH COST-EFFECTIVE RELATIVE TO EXPERIMENTS, SIMULATION OF SPACE VEHICLE OPERATON REQUIRES EXPENSIVE COMPUTER RUNS

- o LATDYN VERSION AND DOCUMENTATION SOON TO BE RELEASED AND WORKSHOP TO BE HELD

REFERENCES

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4. DADS User's Manual, Computer Aided Design Software, Inc., P.O. Box 203, Oakdale, Iowa 52319, 1987.

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6. Adams, L. R.,"Design, Development and Fabrication of A Deployable/Retractable Truss Beam Model for Large Space Structures Application", NASA CR-178287, June 1987.